

A RESEARCH STUDY ON 3-D SOLITON AND PHOTONIC CRYSTAL FIBRE

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Abstract : We present a practical design of novel photonic crystal fibre (PCF) to investigate the nonlinear propagation of femtosecond pulses for the application of optical coherence tomography (OCT) based on super continuum generation (SCG) process. In addition, this paper contains a brief introduction of the physical phenomena of soliton and SCG. Typically, here we discuss how the ultra broadband radiation in PCF can be generated by SCG through various nonlinear effects of the fibre. To accomplish the proposed aim, we put forth liquid core PCF (LCPCF) structure filled with chloroform for OCT measurements of the eye. From the proposed design, we observe that proposed LCPCFs with liquid material exhibit significant broadened wavelength spectrum with low input pulse energy over small propagation distances for the OCT application.

Keywords: Soliton fission, photonic crystal fibre, super continuum generation.

Introduction : The term "soliton" was introduced in the 1960's, but the scientific research of solitons had started in the 19th century when John Scott-Russell observed a large solitary wave in a canal near Edinburgh. Solitons are very stable solitary waves in a solution of those equations. As the term "soliton" suggests, these solitary waves behave like "particles". When they are located mutually far apart, each of them is approximately a traveling wave with constant shape and velocity. As two such solitary waves get closer, they gradually deform and finally merge into a single wave packet; this wave packet, however, soon splits into two solitary waves with the same shape and velocity before "collision".

The stability of solitons stems from the delicate balance of "nonlinearity" and "dispersion" in the model equations. Nonlinearity drives a solitary wave to concentrate further; dispersion is the effect to spread such a localized wave. If one of these two competing effects is lost, solitons become unstable and, eventually, cease to exist. In this respect, solitons are completely different from "linear waves" like sinusoidal waves. In fact, sinusoidal waves are rather unstable in some model equations of soliton phenomena. Computer simulations show that they soon break into a train of solitons.

Definition:

A single, consensus definition of a soliton is difficult to find. Drazin and Johnson (1989) ascribe 3 properties to solitons:

1. They are of permanent form;
2. They are localized within a region;
3. They can interact with other solitons, and emerge from the collision unchanged, except for a phase shift.

More formal definitions exist, but they require substantial mathematics. Moreover, some scientists use the term soliton for phenomena that do not quite have these three properties.

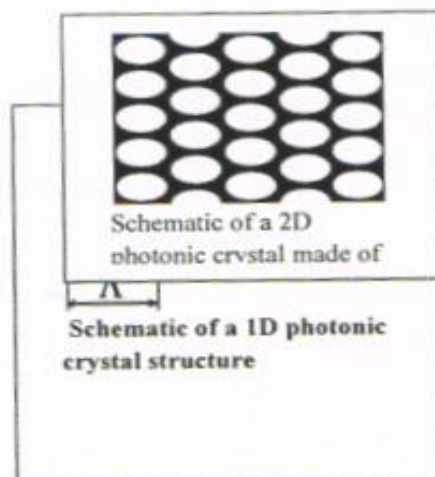
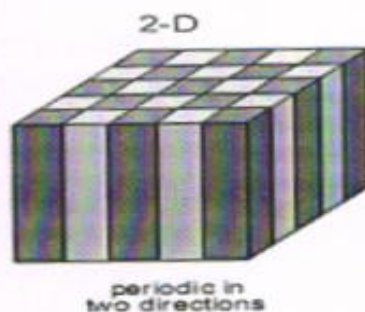
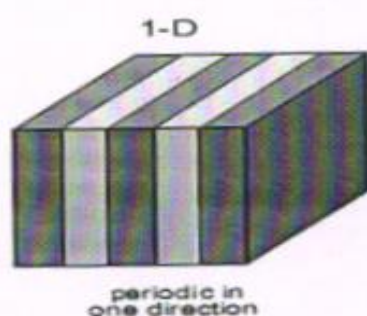
Review

The physics and dynamics of the fundamental discrete and gap solutions are then analyzed along with those of many other exotic classes — e.g. twisted, vector and multi-band, cavity, spatial-temporal, random-phase, vortex, and non-local lattice solutions, just to mention a few. The possibility of all-optically routing optical discrete solutions in 2D and 3D periodic environments using soliton collisions is also presented. Finally, soliton formation in optical quasi-crystals and at the boundaries of waveguide array structures is discussed.

A **photonic crystal** is a periodic optical nanostructure that affects the motion of photons in much the same way that ionic lattices affect electrons in solids. Photonic crystals occur in nature in the form of structural coloration and animal reflectors, and, in different forms, promise to be useful in a range of applications.

In 1887 the English physicist Lord Rayleigh experimented with periodic multi-layer dielectric stacks, showing they had a photonic band-gap in one dimension. Research interest grew with work in 1987 by Yablonovitch and John on periodic optical structures with more than one dimension—now called photonic crystals.

The crystal can thus form a kind of perfect optical "insulator," which can confine light losslessly around sharp bends, in lower-index media, and within wavelength-scale cavities, among other novel possibilities for control of electromagnetic phenomena. Now we introduce the basic theoretical background of photonic crystals in one, two, and three dimensions (schematically depicted in Fig.)



photonic

Strategies of photonic crystals

The fabrication method depends on the number of dimensions that the band gap must exist in.

1. One-dimensional photonic crystal.
2. Two-dimensional photonic crystals.
3. Three-dimensional photonic crystals.

Explanation:

1. One-dimensional Photonic crystal

In a one-dimensional photonic crystal, layers of different dielectric constant may be deposited or adhered together to form a band gap in a single direction. A Bragg grating is an example of this type of photonic crystal. One-dimensional photonic crystals can be either isotropic or anisotropic, with the latter having potential use as an optical switch. One-dimensional photonic crystal can form as an infinite number of parallel alternating layers filled with a met material and vacuum. This produced identical PBG structures for TE and TM modes. Recently, researchers fabricated a grapheme-based Bragg grating (one-dimensional photonic crystal) and demonstrated that it supports excitation of surface electromagnetic waves in the periodic structure by using 633 nm He-Ne lasers as the light source. Besides, a novel type of one-dimensional grapheme-dielectric photonic crystal has also been proposed. This structure can act as a far-IR filter and can support low-loss surface plasmons for waveguide and sensing applications.

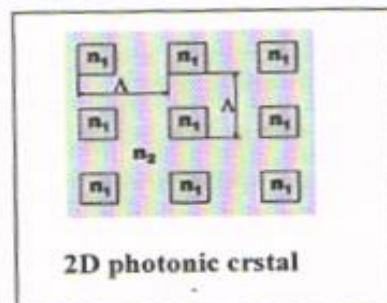
2. Two-dimensional photonic crystals.

In two dimensions, holes may be drilled in a substrate that is transparent to the wavelength of radiation that the band gap is designed to block. Triangular and square lattices of holes have been successfully employed. The Holey fiber or photonic crystal fiber (PCF) is a new class of optical fiber based on the properties of photonic crystals. Because of its ability to confine light in hollow cores or with confinement characteristics not possible in conventional optical fiber, PCF is now finding applications in fiber-optic communications, fiber lasers, devices, high-power transmission, highly sensitive gas sensors, and other be made by taking cylindrical rods of glass in hexagonal lattice, and then and stretching them, the triangle-like air gaps between the glass rods the holes that confine the modes.

3. Three-dimensional photonic crystals.

There are several structure types that have been constructed:

- Spheres in a diamond lattice
- Yablonovite



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- The woodpile structure – "rods" are repeatedly etched with beam lithography, filled in, and covered with a layer of new material. As the process repeats, the channels etched in each layer are perpendicular to the layer below and parallel to and out of phase with the channels two layers below. The process repeats until the structure is of the desired height. The fill-in material is then dissolved using an agent that dissolves the

fill-in material but not the deposition material. It is generally hard to introduce defects into this structure.

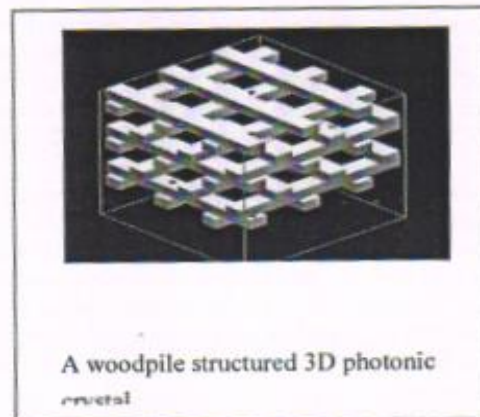
- Inverse opals or Inverse Colloidal Crystals-Spheres (such as polystyrene or silicon dioxide) can be allowed to deposit into a cubic close packed lattice suspended in a solvent. Then a hardener is introduced that makes a transparent solid out of the volume occupied by the solvent. The spheres are then dissolved with an acid such as Hydrochloric acid. The colloids can be either spherical or no spherical.
- A stack of two-dimensional crystals – This is a more general class of photonic crystals than Yablonovite, but the original implementation of Yablonovite was created using this method.
- "The photonic crystal beam splitter that we made is a fundamental optical component used to control polarized light," explains Dr Mark Turner from Swinburne University. "Specifically what makes our device unique is its ability to directly work with circular polarization at a microscopic scale."
- Circular polarization uses 3D laser nanotechnology to exploit circular polarization to build a microscopic prism that contains in excess of 750,000 polymer nimrods. Light focused on this beam splitter penetrates or is reflected, depending on polarization.

Formulation and Variational Analysis of the 3-D model

The model of a three dimensional waveguide corresponding to the outline given above is based on the following variant of 3-D NLS equation of the local amplitude $u(z, x, y, \tau)$ of the electromagnetic field:

$$iu_z - \frac{1}{2}u_{xx} + \frac{1}{2}(u_{yy} + u_{zz}) + \varepsilon[\cos 2x + \cos 2y]u - |u|^2u = 0 \quad (1)$$

Where z is the propagation distance, x and y are the transverse coordinates and t is the reduced time. The signs in front of the group velocity dispersion (GVD) u_{xx} and cubic terms correspond to the normal GVD and self defocusing nonlinearity. ε is the amplitude of the transverse modulation of the refractive index (which more π . total look is assumed sinusoidal but the results will be nearly the same for realistic forms of the modulation which correspond to the actual photonic crystal structure), and period of modulation is scaled to be Dynamical invariants are the norm of the solution (in optics, it is energy). In order to find for the linear spectrum of the model, we for the solutions to be linearized version of eqn. (1) as



A woodpile structured 3D photonic crystal

$$u(z, x, y, \tau) = \exp(i\beta z - i\omega t)[F_E(x) + F_E(y)] \quad (2)$$

where β is the real propagation constant, ω is the arbitrary real eigen value,

$$E = \omega^2 - 2\beta \quad (3)$$

and $F_E(x)$ and $F_E(y)$ are the solution of Mathieu equations.

$$F'' + 2\varepsilon \cos(2x)F + EF = 0 \quad (4)$$

$$F'' + 2\varepsilon \cos(2y)F + EF = 0 \quad (5)$$

Corresponding to the eigen value of E . Since Matheiu eqn. gives rise to band gaps in its own spectrum, i.e., to the forbidden intervals of the value of E , within which no regular quasi-periodic solution of Eq (7) and (8) can be found. However for all large values of E ($E \gg \mathcal{E}$) no value of β may lie in the forbidden bandgap. Indeed any real value of the propagation constant can be constructed as $\beta = (\omega^2 - E)/2$, by taking very large E and accordingly very large ω .

In order to find the stationary solutions for weakly localized soliton shape along x and y and strong ordinary localization in t , we adopt the following variational eqn.

$$u(z, x, y, \tau) = A e^{i\beta z} [x^{-1} \sin ax + y^{-1} \sin by] \sec h(\alpha t) \quad (6)$$

where a, b are transverse, α is longitudinal inverse widths of the soliton and A is the amplitude.

Fig.1: The propagation constant vs. norm of 3-D solitons, as predicted by the variational approximation, eqn. (10) for different values of the strength of

the periodic potential ε and for $N_x = N_y = N$. The negative slope, $d\beta/dN < 0$, implies stability of solitons according to the Vakhitov-Kolokolov criterion.

The stability of 3-D solitons predicted by VK criterion is corroborated by direct numerical simulations. As the VK criterion ignores complex stability eigenvalues, the 3-D solitons may be unstable. More perplexing is the fact that some soliton families in a lattice model with cubic quintic nonlinearity that are formally predicted to be VK unstable, are in reality completely stable.

Results

The physical models of this type emerge in the context of Bose-Einstein condensation (BEC) where the periodic potential is created as an optical lattice (OL), i.e., interference pattern formed by coherent beams illuminating the condensate, and in nonlinear optics, where similar models apply to photonic crystals. A different but allied setting is provided by a cylindrical OL ("Bessel lattice"), which can also support stable 2D and 3D solitons. Additionally, models combining a periodic lattice potential and saturable nonlinearity give rise to 2D solitons and observed in several experiments in photorefractive media, including fundamental solitons and vortices. In models with the cubic nonlinearity, these solutions were investigated in a quasi-analytical form, which combines the variational approximation (VA) to predict the shape of the solitons, and the Vakhitov-Kolokolov (VK) criterion to examine their stability. Final results were provided by numerical methods, relying upon direct simulations of the underlying NLS/GP equations. A conclusion obtained by means of these methods is that, unlike their 1D counterparts, multi-dimensional solitons in periodic potentials can exist only in a limited domain of the (N, ε) plane, where N and ε are the norm of the solution and strength of the OL potential, respectively. The most essential limitation on the existence domain of 2D solitons is that N cannot be too small (in a general form, a minimum value of the norm, as a necessary condition for the existence of 2D solitons supported by lattice potentials). Unlike it, ε may be arbitrarily small, as even at $\varepsilon = 0$ the 2D NLS equation has a commonly known weakly unstable solution in the form of the Townes soliton, at a single value of the norm, $N = N_T$ ($N_T \approx 11.7$ for the NLS equation in the usual 2D form).

Conclusion

The solitons are solutions of a mixed type, as in the free (longitudinal, alias temporal) direction they are regular solitons, while in the transverse direction(s) they are objects of the gap-soliton type (hence the solution as a whole was called a semi-gap soliton). The existence of the solitons requires that both the norm of the solution (in other words, the nonlinearity strength χ) and the strength ε of the spatially periodic transverse potential exceed certain minimum values, otherwise the pulses decay into linear waves. Actually, the solitons are much more sensitive to ε than to χ . The results reported in this paper call for further work, that should be aimed at accurate identification of borders of the solitons' stability regions, especially in the 3D model (which requires running very massive simulations), investigation of collisions between solitons, that may move freely in the longitudinal direction.

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